$E2/M1$ Ratio for the $\gamma N \to \Delta$ Transition in the Chiral Quark Soliton Model

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Abstract

We calculate the electric quadrupole to magnetic dipole transition ratio $E2/M1$ for the reaction $\gamma N \to \Delta(1232)$ in the chiral quark soliton model. The calculated $E2/M1$ ratio is in a good agreement with the very new experimental data. We obtain non-zero negative value for the electric quadrupole $N-\Delta$ transition moment, which suggests an oblate deformed charge structure of the nucleon or/and the delta isobar. Other observables related to this quantity, namely the $N-\Delta$ mass splitting, the isovector charge radius, and isovector magnetic moment, are properly reproduced as well.

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The ratio of electric quadrupole to magnetic dipole amplitude ($E2/M1$) for the reaction $\gamma + N \to \Delta(1232)$ is a quantity sensitive to a presence of charge deformations in the baryon structure. The most reliable phenomenological estimate $E2/M1 = (-1.5 \pm 0.2)\%$ so far comes from detailed analysis [1] of the available photoproduction data, assuming the most general $\gamma N\Delta$ gauge coupling and taking into account the unitary condition via Watson theorem. Very recently a very precise $\pi^{0(+)}$-photoproduction experiment [2] has been performed at MAMI, Mainz, which allows for a direct model-independent estimate of the ratio $E2/M1$. The preliminary result[1] $E2/M1 = (-2.4 \pm 0.2)\%$ [2] confirms the negative sign suggested from the analysis [1] and shows a larger $E2/M1$-asymmetry. This non-zero negative value is a clear indication for the presence of an oblate charge deformation in the nucleon or/and delta and as such it imposes strong constraints for the effective models of baryon structure. Wirzba and Weise have investigated the $E2/M1$ ratio in a modified Skyrme model which includes stabilizing fourth- and sixth-order terms [3]. They obtained values between -5% and -2.5% depending on the coupling parameters of stabilizing terms. However, the other related observables, namely the $N - \Delta$ mass difference, charge radii, and the isovector magnetic moment, are not properly described.

In the present work we study $E2/M1$ ratio for the process $\gamma + N \to \Delta(1232)$ in the chiral quark soliton model (for review see ref. [4]). We employ the simplest SU(2)-version of the model with up and down quark degenerated in mass, which is based on the semibosonized Nambu Jona-Lasinio lagrangean [5,6]:

$$\mathcal{L} = \bar{\Psi}(-i\gamma^\mu \partial_\mu + m_0 + MU^{\gamma_5})\Psi, \tag{1}$$

with auxiliary meson fields

$$U(\vec{x}) = \mathrm{e}^{i\vec{\tau}\cdot\vec{\pi}(\vec{x})/f_\pi}\,, \tag{2}$$

constrained on the chiral circle. The model is non-renormalizable and a finite cutoff is needed. The latter is treated as a parameter of the model and together with the current quark mass m_0 is fixed in the mesonic sector to reproduce the physical pion mass m_π and the pion decay constant f_π. The last model parameter, the constituent quark mass M, can be related to the empirical value of the quark condensate but actually it still leaves a broad range for M.[2]

In the model the baryons appear as a bound state of N_c (number of colors) valence quarks coupled to the polarized Dirac sea. Since the model lacks confinement the proper way to describe the nucleon is to consider [7] a correlation function of two N_c-quark currents with nucleon quantum numbers JJ_3, TT_3 at large euclidean time-separation:

$$\begin{aligned}\lim_{T\to\infty} \Pi_N(T) &= \langle J_N(\vec{x}, +T/2) J_N^\dagger(\vec{y}, -T/2)\rangle \\ &= \frac{1}{Z}\,\Gamma^{\{f\}}_{JJ_3,TT_3}\,\Gamma^{\{g\}*}_{JJ_3,TT_3} \int \mathcal{D}U \prod_{i=1}^{N_c} \langle T/2, \vec{x}|\frac{1}{D}| - T/2, \vec{y}\rangle_{f_i g_i} \mathrm{e}^{N_c \mathrm{Tr}\log D(U)}\,,\end{aligned} \tag{3}$$

[1] In fact, the authors have faced this experimental result after completing the calculations.

[2] Actually, in order to obtain a good description of the baryonic properties the mass M has to be chosen around 420 MeV (see review [4]).

where current J_N is a composite quark operator [8]:

$$J_N(\vec{x},t) = \frac{1}{N_c!}\,\varepsilon^{\beta_1\cdots\beta_{N_c}}\,\Gamma^{\{f\}}_{JJ_3,TT_3}\,\Psi_{\beta_1 f_1}(\vec{x},t)\cdots\Psi_{\beta_{N_c}f_{N_c}}(\vec{x},t)\,. \tag{4}$$

In the above path integral the quark fields are integrated out. The effective action includes the Dirac operator

$$D(U) = i\partial_t - h(U), \tag{5}$$

with one-particle hamiltonian given by

$$h(U) = \frac{\vec{\alpha}\cdot\vec{\nabla}}{i} + \beta M U^{\gamma_5} + \beta m_0\,. \tag{6}$$

In the model the nucleonic solution is obtained in two steps. In the first step, in leading order in N_c the integral over the meson fields U in eq.(3) is done in a saddle point approximation. To that end we look for a stationary localized meson configuration (soliton) of hedgehog structure

$$\bar{U}(x) \;=\; \mathrm{e}^{i\vec{\tau}\cdot\hat{x}\,P(x)}\,, \tag{7}$$

which minimizes the effective action. Actually, the soliton solution is found by solving the corresponding equations of motion in an iterative self-consistent procedure [4]. Since the hedgehog soliton $\bar{U}(x)$ does not preserve the spin and isospin, as a next step we make use of the rotational zero modes to quantize it. It is done assuming a rotating meson hedgehog fields of the form

$$U(\vec{x},t) = R(t)\,\bar{U}(\vec{x})\,R^{+}(t) \tag{8}$$

with $R(t)$ being a time-dependent rotation SU(2) matrix in the isospin space. It is easy to see that for such an ansatz one can transform the effective action

$$\mathrm{Tr}\log D(U) = \mathrm{Tr}\log(D(\bar{U}) - \Omega) \tag{9}$$

in order to separate the angular velocity matrix:

$$\Omega = -iR^{+}(t)\dot{R}(t) = \frac{1}{2}\Omega_a\tau_a\,. \tag{10}$$

Since the angular velocity is quantized according to the canonical quantization rule, it appears as $\Omega_a \sim \frac{1}{N_c}$. This allows one to consider Ω as perturbation and to evaluate any observable as a perturbation series in Ω which is actually an expansion in $\frac{1}{N_c}$. The path integral over $R(t)$, which appears due to the ansatz (8), determines the spin-flavor structure of the nucleonic solution. For given spin J, J_3 and isospin T, T_3 this structure can be expressed through the Wigner D function

$$|N, T_3 J_3\rangle(R) = (-1)^{T+T_3}\sqrt{2T+1}\,D^{T=J}_{-T_3,J_3}(R)\,. \tag{11}$$

Very recently, the nucleon electromagnetic form factors have been calculated [9] in this semiclassical quantization scheme up to the next to leading order in angular velocity. The

results for the constituent quark mass $M \approx 420$ MeV are in fairly good agreement with the experimental data. It should be also noted that the $1/N_c$ rotational corrections improve considerably the theoretical value for the isovector magnetic moment [10].

Obviously it is worthily to consider in this model also the ratio $E2/M1$ for the process $\gamma N \longrightarrow \Delta$ whose value is well settled by the recent experiment in Mainz [2]. It is defined [11] as a ratio

$$\frac{E2}{M1} \equiv \frac{1}{3}\,\frac{M^{E2}(\vec{k},\lambda=+1\ ;\ p(J_3=-\frac{1}{2}) \to \Delta^+(J_3=+\frac{1}{2}))}{M^{M1}(\vec{k},\lambda=+1\ ;\ p(J_3=-\frac{1}{2}) \to \Delta^+(J_3=+\frac{1}{2}))} \tag{12}$$

of electric quadrupole amplitude M^{E2} to magnetic dipole one M^{M1}. Here k is the momentum of a photon of helicity λ in the Δ rest frame:

$$k = \frac{M_\Delta^2 - M_N^2}{2M_\Delta}\,. \tag{13}$$

Both amplitudes are related to the corresponding matrix element of the isovector current:

$$j_3^\mu(\vec{x}) = \bar{\Psi}(\vec{x})\gamma^\mu \frac{\tau_3}{2}\Psi(\vec{x}). \tag{14}$$

For the electric quadrupole amplitude M^{E2}, according to the Siegert's theorem (see for instance [12]), one can use the zero component j_a^0 as well the space component $-\nabla\cdot\vec{j}_a$. Similar to ref. [3] we decide to express the amplitude M^{E2} via the $N-\Delta$ transition matrix element of j_3^0 (charge density) of the current j^μ:

$$M^{E2}(\vec{k},\lambda; N \to \Delta) = \sqrt{15\pi}\int d^3x\ \langle\Delta|j_3^0(\vec{x})|N\rangle Y_{2\lambda}(\hat{x}) j_2(kx), \tag{15}$$

The reason is that in the present model this quantity can be calculated [9] directly in terms of quark matrix elements whereas the for $\nabla\cdot\vec{j}_a$ one should use supplementary the classical equations of motion (saddle point), for which the ansatz (8) is apparently not a solution.

The amplitude M^{M1} is directly related to the $N-\Delta$ transition matrix element of the space components j_a^k:

$$M^{M1}(\vec{k},\lambda; N \to \Delta) = -\lambda\frac{3}{2}\int d^3x \langle\Delta|(\hat{x}\times\vec{j}_3)_\lambda|N\rangle j_1(kx). \tag{16}$$

In the case of $\lambda = +1$, $J_3^p = -\frac{1}{2}$ $J_3^\Delta = +\frac{1}{2}$, we have

$$M^{E2} = +\frac{15\sqrt{3}}{4}\int \mathrm{d}r r^2 j_2(kr)\rho_{N\Delta}^{E2}(r)\,, \tag{17}$$

and

$$M^{M1} = -3\int \mathrm{d}r r^2 j_1(kr)\rho_{N\Delta}^{M1}(r)\,, \tag{18}$$

respectively.

For the matrix element of the isovector current j_3^μ we follow the line of ref. [9] and in fact, we use the results presented there. Here we will only sketch the derivation. We evaluate the

expectation value of the quark bilinear operators, $\Psi^\dagger\gamma^0\gamma^\mu\frac{\tau_3}{2}\Psi$, represented by the euclidean functional integral [7] with lagrangean (1):

$$\langle N',\vec{p}'|\Psi^\dagger(0)\gamma^0\gamma^\mu\frac{\tau_3}{2}\Psi(0)|N,\vec{p}\rangle = \lim_{\substack{T'\to+\infty\\ T\to-\infty}} \frac{1}{Z}\int \mathrm{d}^3x\mathrm{d}^3y \mathrm{e}^{p_4'T'-p_4T-i\vec{p}'\vec{x}'+i\vec{p}\vec{x}}$$
$$\times\int\mathcal{D}U\int\mathcal{D}\Psi\int\mathcal{D}\Psi^\dagger J_{N'}(\vec{x}',T')\,\Psi^\dagger(0)\gamma^0\gamma^\mu\frac{\tau_3}{2}\Psi(0)J_N^\dagger(\vec{x},T)\mathrm{e}^{-\int d^4z\Psi^\dagger D(U)\Psi}\,. \tag{19}$$

Integrating out the quarks in (19) it is easy to see that the result is naturally split in valence and sea parts. After that we follow the same steps as for correlation function (3). First, we integrate over the meson fields in saddle point approximation (large N_c limit). As a second step, we take into account the rotational zero modes using the ansatz (8). Due to the collective path integral over $R(t)$ our scheme[3] involves a time-ordered product of the collective operators

$$\Omega_a(R(t)) = -i\mathrm{Tr}(R^\dagger(t)\dot{R}(t)\tau_a) \quad \text{and} \quad D_{ab}(R(t)) = \frac{1}{2}\mathrm{Tr}(R^\dagger(t)\tau_a R(t)\tau_b)\,, \tag{20}$$

which appear after the expansion in Ω.

In the above scheme the matrix element of the time-component of the isovector current, calculated in the semiclassical quantization scheme, includes only terms linear in $\Omega\sim 1/N_c$

$$\langle\Delta|j_0^3(\vec{x})|N\rangle = \frac{N_c}{2\Theta}\Big\{\sum_{m,n}\mathcal{R}_\Theta^\Lambda(\epsilon_m,\epsilon_n)\Big(\Phi_m^\dagger(\vec{x})\,\tau_a\,\Phi_n(\vec{x})\Big)\,\langle n|\tau_c|m\rangle$$
$$-\sum_{n\neq val}\frac{1}{\epsilon_{val}-\epsilon_n}\Big(\Phi_n^\dagger(\vec{x})\tau_a\Phi_{val}(\vec{x})\Big)\,\langle val|\tau_c|n\rangle\Big\}\langle\Delta,J_3'T_3'|\{J_c,D_{3a}\}|N,J_3T_3\rangle\,, \tag{21}$$

whereas the matrix element of the space-components of the isovector current includes leading order terms $\sim\Omega^0$ as well as next to leading order ones $\sim\Omega$ $(1/N_c)$:

$$\langle\Delta\,|j_3^k(\vec{x})|\,N\rangle = N_c\Big\{\Big(\Phi_{val}^\dagger(\vec{x})\,\gamma^0\gamma^k\tau_a\,\Phi_{val}(\vec{x})\Big)\langle\Delta,J_3'T_3'\,|D_{3b}|\,N,J_3T_3\rangle$$
$$+\frac{i}{2\Theta}\sum_{n\neq val}\mathrm{sign}(\epsilon_n)\frac{\Big(\Phi_{val}^\dagger(\vec{x})\gamma^0\gamma^k\tau_b\Phi_n(\vec{x})\Big)\langle n\,|\tau_c|\,val\rangle}{\epsilon_n-\epsilon_{val}}\langle\Delta,J_3'T_3'\,|[\hat{J}_c\,,\,D_{3b}]|\,N,J_3T_3\rangle$$
$$-\sum_n\mathcal{R}_{M1}^\Lambda(\epsilon_n)\Big(\Phi_n^\dagger(\vec{x})\gamma^0\gamma^k\tau_b\Phi_n(\vec{x})\Big)\langle\Delta,J_3'T_3'\,|D_{3b}|\,N,J_3T_3\rangle$$
$$+\frac{i}{\Theta}\sum_{n,m}\mathcal{R}_{M2}^\Lambda(\epsilon_m,\epsilon_n)\Big(\Phi_m^\dagger(\vec{x})\gamma^0\gamma^k\tau_b\Phi_n(\vec{x})\Big)\langle n\,|\tau_c|\,m\rangle\langle\Delta,J_3'T_3'\,|[\hat{J}_c\,,\,D_{3b}]|\,N,J_3T_3\rangle\Big\}\,. \tag{22}$$

Here Θ is the moment of inertia, and Φ_n and ϵ_n are the eigenfunctions and the eigenvalues of the hamiltonian (6). The regularization functions $\mathcal{R}_\Theta^\Lambda$, $\mathcal{R}_{M1}^\Lambda$ and $\mathcal{R}_{M2}^\Lambda$ can be found in ref. [9].

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[3] The details of this procedure can be found in ref. [9].

For completeness we present the final results for the electric quadrupole density $\rho^{E2}_{N\Delta}(r)$, split in valence and Dirac sea parts,

$$\rho^{E2;val}_{N\Delta}(r) = \frac{N_c}{\Theta}\frac{\sqrt{6\pi}}{90}\sum_{n\neq val}\frac{1}{\epsilon_n-\epsilon_{val}}\ \Big(\Phi_{val}(r)\|[Y_2\otimes\tau^{(1)}]^{(1)}\|\Phi_n(r)\Big)\langle val\|\tau^{(1)}\|n\rangle\,, \tag{23}$$

and

$$\rho^{E2;sea}_{N\Delta}(r) = \frac{N_c}{\Theta}\frac{\sqrt{6\pi}}{180}\sum_{n,m=all}R^{\Lambda}_{\Theta}(\epsilon_n,\epsilon_m)\Big(\Phi_n(r)\|[Y_2\otimes\tau^{(1)}]^{(1)}\|\Phi_m(r)\Big)\langle n\|\tau^{(1)}\|m\rangle \tag{24}$$

as well as for the magnetic density $\rho^{M1}_{N\Delta}(x)$:

$$\rho^{M1;val(\Omega^0)}_{N\Delta}(r) = -N_c\frac{i}{6\sqrt{6}}\Big(\Phi_{val}(r)\|\gamma_5[[\hat{x}^{(1)}\otimes\sigma^{(1)}]^{(1)}\otimes\tau^{(1)}]^{(0)}\|\Phi_{val}(r)\Big)\,, \tag{25}$$

$$\rho^{M1;sea(\Omega^0)}_{N\Delta}(r) = -N_c\frac{i}{12\sqrt{6}}\sum_{n=all}R^{\Lambda}_{M1}(\epsilon_n)\sqrt{2K_n+1}\Big(\Phi_n(r)\|\gamma_5[[\hat{r}^{(1)}\otimes^{(1)}\sigma]^{(1)}\otimes\tau^{(1)}]^{(0)}\|\Phi_n(r)\Big)\,, \tag{26}$$

$$\rho^{M1;val(\Omega^1)}_{N\Delta}(r) = -\frac{N_c}{\Theta}\frac{i}{36}\sum_{n\neq val}\frac{\mathrm{sign}(\epsilon_n)}{\epsilon_n-\epsilon_{val}}\Big(\Phi_{val}(r)\|\gamma_5[[\hat{r}^{(1)}\otimes\sigma^{(1)}]^{(1)}\otimes\tau^{(1)}]^{(1)}\|\Phi_n(r)\Big)\langle val\|\tau^{(1)}\|n\rangle, \tag{27}$$

$$\rho^{M1;sea(\Omega^1)}_{N\Delta}(r) = -\frac{N_c}{\Theta}\frac{i}{72}\sum_{n,m=all}R^{\Lambda}_{M2}(\epsilon_n-\epsilon_m)\Big(\Phi_n(r)\|\gamma_5[[\hat{r}^{(1)}\times\sigma^{(1)}]^{(1)}\times\tau^{(1)}]^{(1)}\|\Phi_m(r)\Big) \times\langle n\|\tau^{(1)}\|m\rangle\,. \tag{28}$$

On the other hand, using (15) and (16) in the approximation $k\cdot R\ll 1$, where R is the nucleon charge radius, we get following simple formulae

$$M^{E2} = -\frac{3}{4\sqrt{2}}k^2\langle Q_{zz}\rangle_{N\Delta}, \tag{29}$$

$$M^{M1} = -\frac{k}{\sqrt{2}}\frac{1}{2M_N}\ \mu_{N\Delta}, \tag{30}$$

where $\langle Q_{zz}\rangle_{N\Delta}$ is the electric quadrupole transition moment and $\mu_{N\Delta}$ is the transition magnetic moment:

$$\mu_{N\Delta} = \frac{1}{\sqrt{2}}\mu_{I=1}\,. \tag{31}$$

Here $\mu_{I=1}=\mu_p-\mu_n$ is the isovector magnetic moment. Using (29) and (30), in the $k\cdot R\ll 1$ approximation one can relate the ratio $E2/M1$ to the electric quadrupole $N\Delta$ transition moment:

$$\frac{E2}{M1} = \frac{1}{2} k M_N \frac{\langle Q_{zz} \rangle_{N\Delta}}{\mu_{N\Delta}} \,. \tag{32}$$

It should be noted that in contrast to the Skyrme model, $\langle Q_{zz} \rangle_{N\Delta}$ cannot be directly related to the isovector charge radius. The corresponding transition charge density $\rho^{E2}_{N\Delta}(x)$ has a more complicated structure, including a spherical harmonics tensor $Y_{2\mu}$, which acts on the quark wave function as a projector for the charge deformation.

In the numerical computations we use the method of Ripka and Kahana [13] for solving the eigenvalue problem in a finite quasi–discrete basis.

In table I, we present our results for the ratio $E2/M1$ as well as for some related observables, namely the isovector charge m.s.radius, the $N - \Delta$ transition magnetic moment $\mu_{N\Delta}$, the $N - \Delta$ mass difference, and the quadrupole electric transition moment $\langle Q_{zz} \rangle_{N\Delta}$, for three different values of the constituent quark mass M. We compare our results with the experiment as well as with the numbers of ref. [3]. With constituent quark mass M around 420 MeV we obtain for the $E2/M1$ ratio values between -2.5% and -2.3% quite in agreement with the last experiment data [2]. It should be mentioned that for the same values of the constituent quark mass M the nucleon properties (including also the nucleon form factors) are reproduced fairly well [9]. The only exception is the $N - \Delta$ transition magnetic moment which is underestimated by 25%. Our results for other observables in table I show an overall good agreement with the experiment which, however, is not the case for the Skyrme model calculations [3]. The Skyrme model results show a strong underestimation of the isovector charge radius and $N - \Delta$ mass splitting whereas the isovector magnetic moment is strongly overestimated.

In the table I we also present the results for the ratio $E2/M1$ in the $k \cdot R \ll 1$ approximation. Despite that this approximation is not justified it seems that it works in practice satisfactorily: the numbers using the formula (32) overestimate the exact results by not more than 20%. From the relation (32) we also get a rough estimate for the electric quadrupole transition moment $\langle Q_{zz} \rangle_{N\Delta} = -0.026$ using the experimental values for $E2/M1 = -2.4 \pm 0.2$ [2] and $\mu_{N\Delta} = 3.3$, which is not far from our model prediction -0.02. This negative non-zero value indicates a presence of an oblate type of charge deformations in the nucleon or/and delta structure. It is interesting to mention that the dominant contribution to the $\langle Q_{zz} \rangle_{N\Delta}$ in the NJL model comes from the Dirac sea. It can be seen in the table I as well on the figure 1, where the electric quadrupole transition moment density, separated in valence and Dirac sea parts, is shown. It means that the main charge deformation is due to the polarized Dirac sea, whereas the valence quarks are almost spherically distributed. Since using the gradient expansion, the polarization of the Dirac sea can be expressed in terms of the dynamical pion field – pion cloud, one can think of the nucleon or/and of the delta as consisting of an almost spherical valence quark core surrounded by a deformed pion cloud.

In summary, we study the electric quadrupole to magnetic dipole transition ratio $E2/M1$ for the reaction $\gamma N \to \Delta(1232)$ in the chiral quark soliton model. The calculated $E2/M1$ ratio for the constituent mass around 420 MeV is in a good agreement with the very new experimental data. We obtain a non-zero negative value for the electric quadrupole transition moment, which suggests an oblate deformed charge structure of the nucleon or/and for the delta isobar. Other related observables, namely the $N - \Delta$ mass difference, the isovector charge radius, and the $N - \Delta$ transition magnetic moment, are properly reproduced as well.

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FIGURES

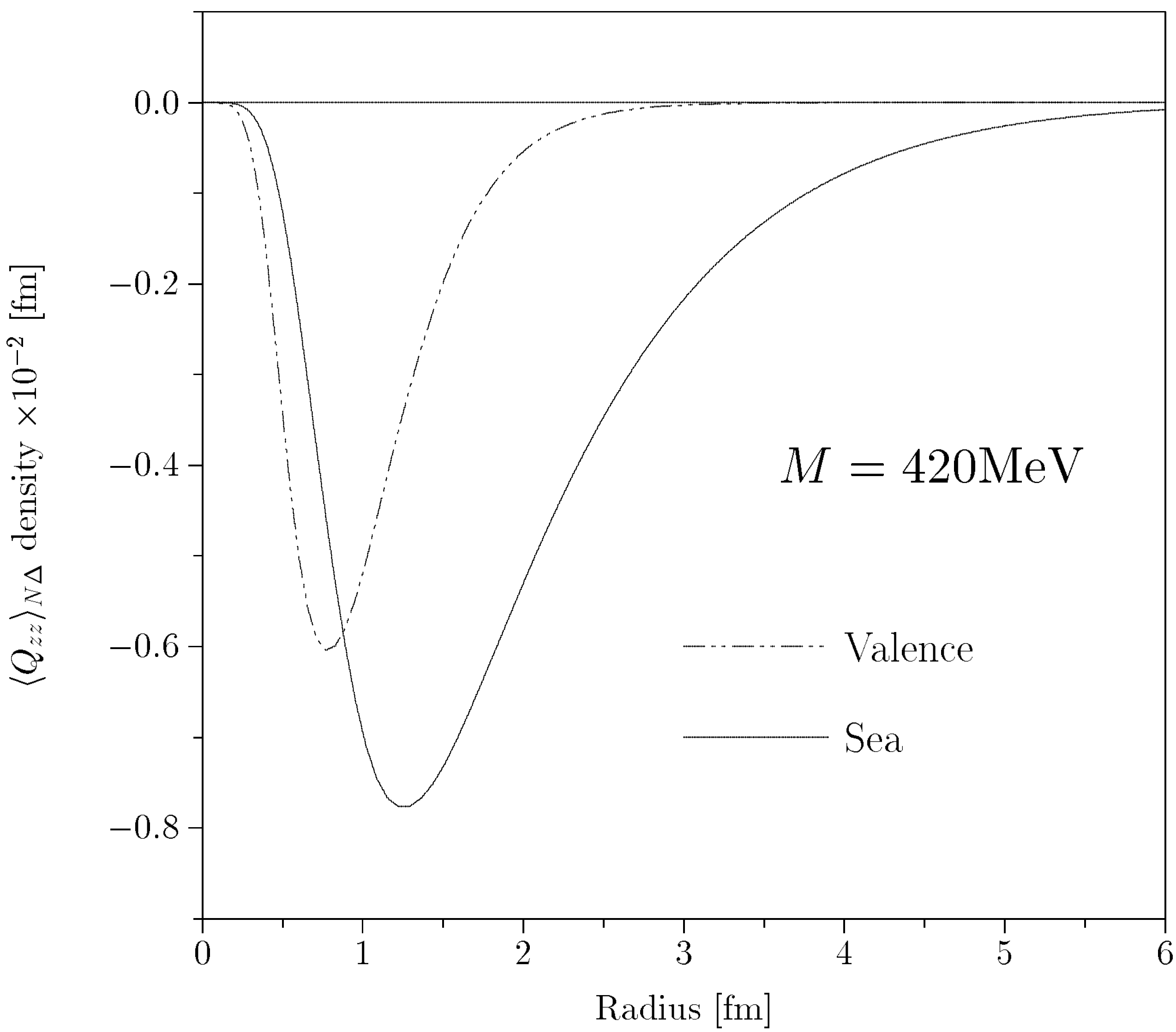
FIG. 1. Electric quadrupole $N-\Delta$ transition moment densitiy, separated in valence and Dirac sea parts.

TABLES

TABLE I. Ratio $E2/M1$ and some related observables, calculated in the NJL model for three different values of the constituent mass$M = 400, 420$ and 450 MeV, compared with experimental values. The Skyrme model results [3] are also presented.

Quantity	**Constituent quark mass M** 400 MeV		420 MeV		450 MeV		**Skyrme**	**Exper.**
	total	sea	total	sea	total	sea		
$\langle r^2\rangle_{I=1}$ [fm^2]	0.88	0.35	0.84	0.37	0.79	0.41	0.60	0.86
$\mu_{\Delta N}$ [$n.m.$]	2.34	0.57	2.28	0.58	2.20	0.60	6.18	3.33
$M_\Delta - M_N$ [MeV]	255		278		311		199	294
$\langle Q_{zz}\rangle_{\Delta N}$ [fm^2]	-0.020	-0.014	-0.020	-0.015	-0.021	-0.016	-0.028	-0.026[4]
M^{E2}	0.012	0.008	0.013	0.008	0.013	0.009		
M^{M1}	-0.189	-0.041	-0.186	-0.042	-0.182	-0.043		
$E2/M1$ [%]	-2.19		-2.28		-2.42		-2.6	-2.4 ± 0.2
$E2/M1$ [%][4]	-2.64		-2.79		-2.99			-2.4 ± 0.2

[4]Using eq.(32)



$\langle Q_{zz} \rangle_{N\Delta}$ density $\times 10^{-2}$ [fm]
0.0
−0.2
−0.4
−0.6
−0.8
0
1
2
3
4
5
6
Radius [fm]
$M = 420\text{MeV}$
Valence
Sea